Design and Testing of a One Dimensional Measuring Machine for Determining the Length of Ball Bars

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INTRODUCTION

One of the most common artifacts used to evaluate the volumetric measuring performance of coordinate measuring machines is the ball bar (ANSI/ASME B89.1.12M). This procedure involves measuring the distance between two precision spheres which are held a fixed distance apart by the connecting rod of the ball bar. The measurement is repeated at numerous positions and orientations in the workspace of the machine. Because the ball bar is a fixed length, any deviations in the measured center distance are an indication of measuring errors of the CMM. When used for this purpose, the absolute length of the ball bar need not be known. However, if the CMM measurement value is to be compared to a known length standard to establish traceability, then the calibrated length of the ball bar is required. The current best method for certifying the length of ball bars is by measurement on very high performance CMMs. This procedure is expensive and time consuming, and is unsuitable for adoption by individual corporate standards laboratories.

The goal of the work reported here is to provide a simpler and lower cost instrument capable of measuring the absolute length of ball bars ranging from 300 to 1000 mm nominal length with an expanded uncertainty for the measurement of $U=0.2 + 0.2L$ μm, where L is given in meters. An additional goal is to design an instrument which does not act as a length comparator, thus requiring a calibrated ball bar to "master" the machine, but introduces the length metric directly into the measurement process.

DESIGN CONCEPT

The instrument we have developed is essentially a 1 dimensional measuring machine (1DMM). It is composed of a long stiff granite beam (approx. 150mm X 300mm X 2000mm) with 2 air bearing stages riding on its top surface (Figure 1). Each stage carries a kinematic mount to accept the end of a ball bar, and a retroreflector mounted so that its center is coaxial with the axis of the ballbar. A fixed block at the center of the beam holds another kinematic mount to accept a ball bar end. A metrology frame is kinematically mounted to the top of the granite beam. The metrology frame consists of two endplates connected by 3 Invar rods. Each endplate of the metrology frame holds a Michelson interferometer whose measurement axis is aligned with the ballbar axis and stage motion, thus minimizing Abbe errors during measurement. (Figure 2)

The granite beam is sized so that deflections due to the weight of the ball bar and the moving sled cause negligibly small errors in the measurements. Appropriate adjustment degrees of freedom are provided on the sleds and optical mounts to allow the three kinematic mounts to be aligned in a straight line and the interferometer beams to be aligned to the stage motions.

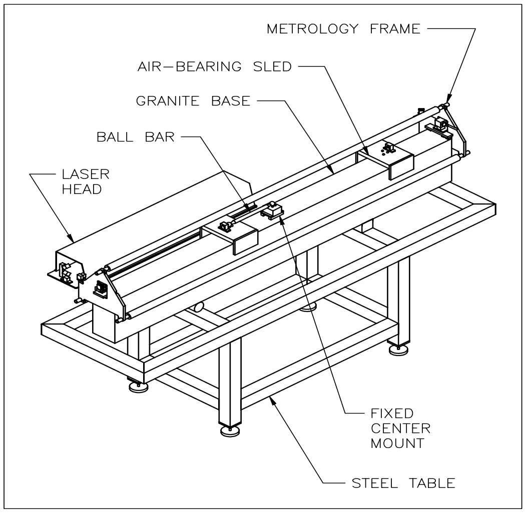

Figure 1. Conceptual design of 1DMM

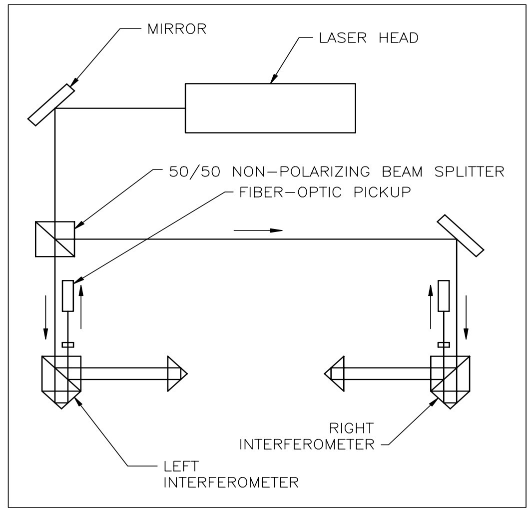

Figure 2. Interferometer layout of 1DMM

The measurement procedure, which does not require a separate calibrated artifact to "master" the gage, is as follows:

1. Place the ball bar ends in the kinematic mounts on the left movable stage and fixed center point and initialize the left interferometer to zero.
2. Move the right end of the ball bar to the right movable stage, and simultaneously initialize the right interferometer to zero and record the displacement, ***a***, measured by the left interferometer.
3. Move the left end of the ball bar to the fixed center mount and record the displacement, ***b***, of the right interferometer.
4. The length between ball centers of the ball bar is ***L = a + b***.

UNCERTAINTY ANALYSIS

An uncertainty analysis was carried out for the design which takes into account laser system errors, environmental effects, stage misalignments and error motions, cosine and Abbe' errors of the measurement beam, thermal effects in the ballbar and metrology frame, sag of the ball bar, and mechanical repeatability of the system. (Table 1) The assumed measurement conditions for the uncertainty analysis are:

1. Room at 20 °C ± 0.05 °C.
2. Temperature of air and ballbar measured to ±0.01 °C.
3. Barometric pressure measured to ±0.255 mm Hg (34 Pa).
4. Relative humidity measured to ± 5%.
5. Uncertainty of CTE of material = 1 ppm / °C.
6. Negligible vibrations.
7. Dead path length for each interferometer = 10 mm.

8. CO_2 content of atmosphere = 355 ppm
9. Time required for complete measurement is assumed to be less than 10 minutes.

Table 1. Uncertainty analysis for a 1000 mm ballbar measurement.

Source of Uncertainty	Standard uncertainties from random effects in the current measurement process (μm)		Standard uncertainties from systematic effects in the current measurement process (μm)	
	Type A evaluation	Type B evaluation	Type A evaluation	Type B evaluation
Wavelength stability		.027		
Polarization mixing				.00164
Resolution				.00124
Environmental Error		.161		
Deadpath Error				.001
Stage Misalignment				.02
Laser Alignment				.007
Thermal Errors		.176		
Ball Sphericity				0.1
Ball Bar Sag				.07

Combined Standard Uncertainty: u_c = 0.270 μm
Expanded Standard Uncertainty: $U = 2\ u_c$ = 0.540 μm
Target Expanded Standard Uncertainty: U = 0.400 μm

Although the uncertainty analysis shows that the target expanded uncertainty is not met, it can be seen that the most significant contributors to the error are environmental and thermal effects. Changes in the basic design of the machine will have a small effect on these sources of error. Therefore, it was decided to build and test a prototype 1DMM to assess its accuracy and repeatability.

TEST RESULTS

Figure 3 shows a photograph of the prototype 1DMM. The instrument was delivered to NIST and assembled in a room with the temperature controlled to approximately +/-0.05˚C. The temperature, pressure, and humidity of the air were monitored and appropriate corrections to the index of refraction were made using Edlen's equation. The temperature of the ball bar was also monitored and its length corrected using the best available estimate of the CTE. Noise and drift tests were performed to assess the stability of the instrument and to

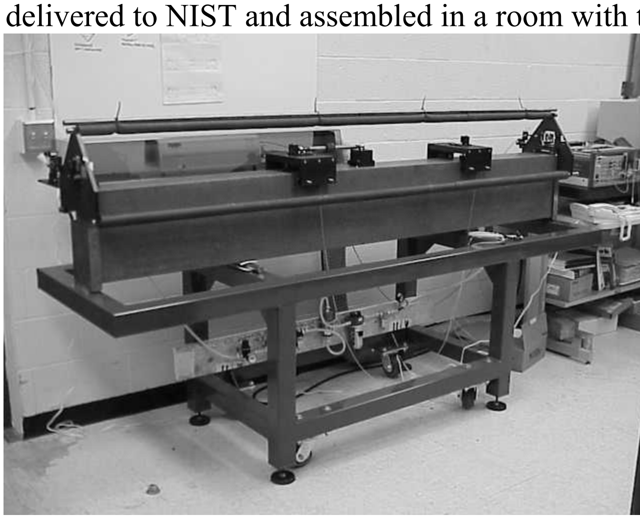

Figure 3. Prototype 1DMM

determine the optimal sampling time for interferometric measurements. Based on these tests, it was decided to read the laser interferometers by sampling them 150 times over a 15 second period and averaging the readings. This procedure was selected to reduce the sensitivity of the measurements to variations in the air along the laser path due to imperfect mixing of the air in the room, yet still be rapid enough to minimize the effect of thermally induced changes in the instrument components.

Six ball bars of varying lengths and materials were measured by NIST on their Moore M-40 CMM. These ball bars were then measured on the 1DMM. Each ball bar was measured 10 times in succession, which required approximately 30 minutes. The measured length of the ball bar is reported as the mean of the 10 measurements. Table 2 shows the results of these measurements.

Table 2. Results of 1DMM measurement of 6 ball bars. (All lengths in mm)

Ball bar material	Nominal length	1DMM length	1DMM 2*S.D.	NIST measured length	1DMM length – NIST length
Steel	400	400.54437	0.00020	400.54454	-0.00017
Invar	400	400.09760	0.00017	400.09759	0.00001
Invar	500	499.93388	0.00030	499.93403	-0.00015
Invar	600	599.98659	0.00021	599.98635	0.00014
Steel	700	698.90277	0.00015	698.90290	-0.00013
Invar	900	899.93887	0.00025	899.93857	0.00030

In all cases the 1DMM measurements were within 0.30 µm of the NIST measured lengths. The expanded uncertainties (K=2) of the 1DMM measurements were all less than 0.25 µm. This is significantly less than predicted by the uncertainty analysis, and is most probably due to better environmental conditions than were assumed in that analysis. Furthermore, in all cases the uncertainty obtained for these measurements is less than the target value established at the beginning of the project.

The 1DMM achieves satisfactory results as a special purpose machine for highly accurate certification of the length of ball bars at a small fraction of the cost of high accuracy, general purpose CMMs.

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